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**"Adaptive Optics Imaging of Solar System Objects"**

**January 1, 1997 to December 31, 1997**

**Submitted by**

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## 1997 PROGRESS REPORT

**GRANT TITLE:** Adaptive Optics Imaging of Solar System Objects

**PRINCIPAL INVESTIGATOR:** François Roddier (Co-Investigator: Toby Owen)

**INSTITUTION:** Institute for Astronomy (IfA), University of Hawaii (UH).

### ABSTRACT

#### Goals:

Most solar system objects have never been observed at wavelengths longer than the R band with an angular resolution better than 1". The Hubble Space Telescope itself has only recently been equipped to observe in the infrared. However, because of its small diameter, the angular resolution is lower than that one can now achieved from the ground with adaptive optics, and time allocated to planetary science is limited. We have been using adaptive optics (AO) on a 4-m class telescope to obtain 0.1" resolution images solar system objects at far red and near infrared wavelengths (0.7–2.5  $\mu\text{m}$ ) which best discriminate their spectral signatures. Our efforts has been put into areas of research for which high angular resolution is essential, such as the mapping of Titan and of large asteroids, the dynamics and composition of Neptune stratospheric clouds, the infrared photometry of Pluto, Charon, and close satellites previously undetected from the ground.

#### Progress and Accomplishments:

- 1) An eclipse of Epimetheus was photometrically analyzed, giving new constraints on the F ring structure and opacity as well as on the inclination of Epimetheus' orbit (Fig. 1).
- 2) Discovery of an arc of particles near Enceladus' orbit, a transient phenomenon possibly produced by collisions of ice blocks which may be at the origin of the E ring (Fig. 2).
- 3) First AO observations of active volcanoes on Io. More than half a dozen heat spots have been detected. Most have been identified with known surface features (Fig. 3).
- 4) Mapping of Neptune tropospheric and stratospheric clouds at 6-month intervals. Images will allow us to estimate wind speeds and monitor Neptune's atmospheric activity (Fig. 4).
- 5) Independent infrared photometry of Pluto and Charon showing differences in surface composition and heterogeneities. Evidence for an excess of ice on Charon (Fig. 5).
- 6) Surface mapping of Ceres, Pallas and Vesta showing heterogeneities in surface composition.
- 7) First observations with a new enhanced 36-actuator AO system (Fig. 6). Older components have been donated to NASA IRTF for the construction of a user AO instrument.

#### Anticipated Accomplishments:

- 1) *Thermal imaging of Io.* Additional observing time has been awarded for this project in June 1998 at the CFHT.
- 2) *Mapping of Titan.* New images of Titan obtained in November 1997 with the new 36-actuator UH AO system will be processed and analyzed.
- 3) *Observations of Neptune.* One and a half night has been awarded in June 1998 at the CFHT to observe Neptune with the new 36-actuator UH AO system. We will attempt to detect and analyze photometrically most of Neptune's faint inner satellites, follow the motion of Neptune's clouds over a sufficiently long period of time to determine wind speed as a function of both latitude and altitude, and search for the sources of auroral emissions
- 4) *Individual photometry of Pluto and Charon.* Additional observing time has been awarded for this project in June 1998 at the CFHT. We expect to cover the entire surfaces of both Pluto and Charon, and search for possible variations in the frost coverings.
- 5) *Asteroids.* From images of Vesta taken in November 1997 with the new 36-actuator UH AO system we expect to produce the first geological map of an asteroid made from the ground, with an unprecedented resolution (even from space).

## Relevant Publications

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- Roddier, C., Roddier, F. "Photometric analysis and modeling of the August 1995 Saturn ring HST data," paper presented at the Wellesley workshop (July 25-26, 1997). Abstract edited by M. Showalter, P. Nicholson, D. French.
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- Roush, T., Cruikshank, D., Owen, T.: "Surface Ices in the Outer Solar System", in *Volatiles in the Earth and Solar System*, AIP Conference Proceedings **341** (ed. K. A. Farley, New York: AIP Press), pp. 143-153, 1995.
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- Stansberry, J. A., Spencer, J. R., Howell, R. R., Dumas, C., Vakil, D. "Violent Silicate Volcanism on Io in 1996", Geophys. Res. Letters. **24**, pp. 2455-2458, 1997.

## PROGRESS and ACCOMPLISHMENTS

The University-of-Hawaii adaptive optics (AO) system has been regularly used on the 3.6-m Canada-France-Hawaii Telescope (CFHT) for planetary observations. The system, which has recently been upgraded to 36-actuators, is equipped with two cameras, a 1024 x 1024 pixels HgCdTe infrared camera built at the Institute for Astronomy (IfA), and a 1024 x 1024 pixels CCD camera. It routinely produces diffraction-limited images at wavelengths ranging from 2.2  $\mu\text{m}$  down to 0.8  $\mu\text{m}$ . We give here a progress report on the results obtained to date at the Institute for Astronomy (IfA) in the field of planetary sciences. Results are from observations made over the last three year, starting from observations made in August 1995, as the Earth was crossing Saturn's ring plane, and ending with observations made in November 1997 with the upgraded AO system.

### 1. 1995 Saturn ring-plane crossing

Further progress has been made in reducing our August 1995 ring plane crossing data. Results were presented at the July 1997 Wellesley workshop organized by Mark Schowalter, Phil Nicholson, and Dick French. We summarize them below:

- 1) Evidence was found for a dozen objects, probably clumps, orbiting Saturn at the distance of the F ring. Among these objects two of them have been identified with objects 1995 S5 and S7 observed by HST (see IAU circular 6515 and last year progress report).
- 2) Photometric ring profiles were obtained as a function of distance to Saturn, and the intensities were compared to that of a perfect Lambert diffuser. The profile time evolution has been modeled. The gap between the A ring and the F ring is found to contribute to the profiles with a vertical optical thickness of  $10^{-4}$ . Evidence is also found for a composite structure in the F ring with a geometrically thick component of very low particle density (paper in preparation).
- 3) An eclipse of Epimetheus was observed over about 10 minutes and photometrically analyzed. We determined that Epimetheus was passing through the shadow produced by ring particles extending from the F ring to the Encke division. The results give new constraints on the F ring structure and opacity as well as on the inclination of Epimetheus' orbit. See Fig. 1 in this report.
- 4) An arc of particles was discovered on a Keplerian orbit close to that of Enceladus (see IAU circular 6697). It appears to be a transient phenomenon possibly due to a collision between an ice block ejected from Enceladus and ice fragments trapped near a Lagrange point (paper submitted to Icarus). See Fig. 2 in this report.

### 2. Io

Volcanism on Io is active and diverse. One type of eruption involves molten sulfur whose temperature cannot exceed 550 K (Sinton et al. 1980) while another type, produced at higher temperature ( $> 1000^\circ\text{K}$ ), is more violent and implies ejection of silicates. We have started a program of high angular resolution imaging of the thermal emission produced by volcanism on . Fig. 3 shows a 2.26  $\mu\text{m}$  image of Io during an eclipse in the shadow of Jupiter. Obtained on July 97 with the 13-actuator UH AO system, this image shows the Jupiter-facing hemisphere of Io with a resolution better than that of the images of the same hemisphere obtained at similar wavelengths with the NIMS spectro-camera aboard the Galileo spacecraft. This ground-based program will help us locate hot spots and identify active calderas on this hemisphere of Io. Comparison of images taken at different dates will give information on the long-term evolution of these hot-spots and will provide constraints on the eruption mechanisms, which may include fire fountains and overturning lava lakes (Stansberry et al. 1997).

### 3. Neptune

New images of Neptune have been obtained in October 1996 and July 1997 with the UH 13-actuator AO system, and in November 1997 with the new UH 36-actuator AO system. These images have allowed us to keep track of Neptune cloud activity. Images were recorded both in and out of the methane absorption bands showing different cloud structures. Images taken in the methane bands show high contrast stratospheric clouds, whereas images taken outside the methane bands show both tropospheric and stratospheric clouds. Fig. 4 show an example of Neptune's stratospheric cloud activity. Such images will allow us to determine the rotation speed of Neptune's atmosphere as a function of both altitude and latitude. They will also allow us to monitor long term changes in Neptune's cloud activity.

### 4. Pluto and Charon

Because Pluto and Charon are always less than 0.9" apart, most compositional observations of the planet and its satellite have been made with the combined light of the two bodies. Assuming that the contribution of Charon to the combined light was negligible, the surface of Pluto was found to be covered by a mixed deposit of ices of  $N_2$ , CO, and  $CH_4$ , with no evidence of  $H_2O$  (Owen et al. 1993). In 1987 and 1988, when occultations allowed light from Pluto to be subtracted from the sum of Pluto plus Charon, this difference indicated that the surface of Charon is coated with  $H_2O$  ice, but no other species have been confirmed (Buie et al. 1987, Fink & Desanti 1987, Marcialis et al. 1987)). If this is true, it is a major constraint on models for the origin and evolution of this system. However, these results are not definitive (Roush 1995). Adaptive optics has allowed us to improve this situation. Our previous (1996) observations showed that it is possible to separate Pluto and Charon cleanly at the focal plane. In July 1997, we used narrow band filters to isolate the  $H_2O$  ice absorption at 1.55  $\mu m$ , the continuum at 1.33  $\mu m$ , the  $H_2O$  absorption at 2.0  $\mu m$ , and the  $CH_4$  absorption at 2.35  $\mu m$ . The observations were successful and we are presently analyzing the data. Simple visual inspection of the images (Fig. 5) supports the earlier results: It indeed appears that Charon is singularly free of methane frost. This is a very surprising result, in view of the fact that both Pluto and Triton are coated with methane.

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### 5. Asteroids

We obtained this year extremely good results using adaptive optics on CFHT to observe surfaces of minor bodies of the solar system: Ceres, Pallas and Vesta. The results presented below are preliminary since the data were obtained only recently and a full analysis is currently in progress.

#### *Ceres and Pallas.*

These two asteroids were observed in July 1997 while their angular diameter was respectively 0.55" and 0.24". The 13-actuator version of the UH AO system and the UH Nicmos camera QUIRC were used. Diffraction limited images of their surface were obtained through narrow band filters centered in and out of the absorption bands of water ice. The main purpose of these observations was to measure the distribution of bound water on the surface of Ceres and

Pallas. Indeed, the reflection spectrum of some metamorphic asteroids displays an absorption band near 3.0 micron that could be attributed to the presence of water molecules trapped between the minerals that form the regolith. The interior of such objects could retain some water that migrates outward to continuously replenish the surface. Ceres, the largest main belt asteroid, displays a very strong absorption band in its reflection spectrum (Lebofsky et al. 1981) and calculation made by Fanale and Salvail (1989) showed that pure water-ice could even be present at high latitudes on Ceres. Differences in the surface albedo of Ceres are indeed visible between the two wave bands, which may be due to a local concentration of ice. Similar results were obtained on Pallas. In addition to the measurements of the water distribution on the surface of these two asteroids, these data will lead to a direct measurement of their size and direction of their rotation axis.

#### *Vesta:*

Asteroid 4 Vesta is particularly interesting since it is the only main belt asteroid that is mineralogically differentiated and that has survived catastrophic collisions. This asteroid could be the source of the howardite, eucrite and diogenite (HED) meteorites (Binzel and Xu, 1993), although Cruikshank et al. 1981 reported a good match between the reflection spectra of three Earth-approaching asteroids and the basaltic achondrites. Imaging Vesta's through narrow band filters that match the absorption bands of the main minerals present on its surface will allow us to study the earliest stages of differentiation on a body similar to the planetesimals from which the terrestrial planets formed.

#### *Early observations.*

Narrow band images of Vesta were obtained during the two last oppositions (Dumas et Hainaut, 1996; Dumas 1997). New estimates have been obtained for the dimensions of Vesta (550 km x 530 km x 440 km). In particular, the 1996 images show that the shape of Vesta departs strongly from an ellipsoid near the south pole. Although the rotational coverage was not total, we were able to produce a partial map of its surface and the ratio of the maps obtained through different narrow band filters that match the 0.9 micron absorption band of pyroxene, shows an increase in the depth of this band for negative latitudes. The current interpretation, confirmed by the HST observations of Vesta (Thomas et al. 1997; Binzel et al. 1997), is that the peculiar shape of the south pole is due to an impact crater that is suspected to be at the origin of the formation of the family of small "Vestian" asteroids. The ground-based images show that this impact excavated material (diogenites) from the mantle. The diogenites cover a large part of the southern hemisphere of Vesta, up to equator latitudes. All these results are presented in Dumas's PhD thesis (Dumas, 1997) and a paper will soon be submitted.

#### *The observations of November 1997:*

The goal of the 1997 observations was to map the full surface of Vesta in the near-infrared with unprecedented spatial resolution. Indeed the visible (0.7--0.9) micron images obtained in 1996 could not return information about the abundance of other minerals (in addition to the pyroxene) suspected to be present on Vesta: olivine and feldspar. Only the mapping of Vesta in the near-infrared would allow us to discriminate between these minerals. Our observations have just been completed at the 3.6-m CFH telescope using the new upgraded UH AO system with 36 actuators. We reached the limit of diffraction all nights down to I band and were able to obtain a very fine coverage of Vesta's surface through 6 narrow band filters at 0.9, 1.1, 1.25, 1.5, 1.71 and 1.99 microns that match the absorption band of pyroxene, feldspar and olivine. Our longitudinal sampling was most of the time close to 10 degrees and never exceeded 30 degrees. The resolution of these unequaled, even from space.

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## ANTICIPATED ACCOMPLISHMENTS

### 1. 1995 Saturn ring-plane crossing

Two papers are in preparation, one describing our observations of clumps in the F ring (see IAU circular 6515 and last year report) and our analysis of an eclipse of Epimetheus (see this report). A second paper will deal with the photometry and modeling of the ring brightness variations during the crossing (results presented at the Wellesley workshop).

### 2. Io

Additional observing time has been awarded for this project in June 1998 at the CFHT.

### 3. Neptune

A total of one and a half night has been awarded in June 1998 at the CFHT to observe Neptune with the new 36-actuator UH AO system. The following observations will be attempted:

- 1) *Detection and photometry of faint satellites.* We expect to detect most of the faint inner satellites observed by Voyager and measure their infrared albedos. We will also look for possible other previously undetected satellites, further away from Neptune.
- 2) *Neptune's cloud dynamics.* We will be able to follow the motion of Neptune's clouds over a sufficiently long period of time to determine wind speed as a function of both latitude and altitude.
- 3) *Search for auroras.* Observations through narrow band filters centered on the  $H_3^+$  emission lines should enable us to accurately locate the source of the emissions. Because Neptune's magnetic axis is inclined and displaced from its rotation axis, auroral halos are expected to occur at mid latitudes rather than at the poles.

### 4. Pluto and Charon

We expect to complete the analysis of the 1997 data in another month. These observations have been so successful that we are looking into the possibility of refining them by means of additional filters with narrower band widths. We also want to extend the data set over a longer time sequence, so we can cover the entire surfaces of both Pluto and Charon, to search for possible variations in the frost coverings.

## **5. Asteroids**

Images of Vesta taken in November 1997 with the new 36-actuator UH AO system will be processed and fully analyzed, establishing the first geological map of an asteroid made from the ground, with an unprecedented resolution (even from space).

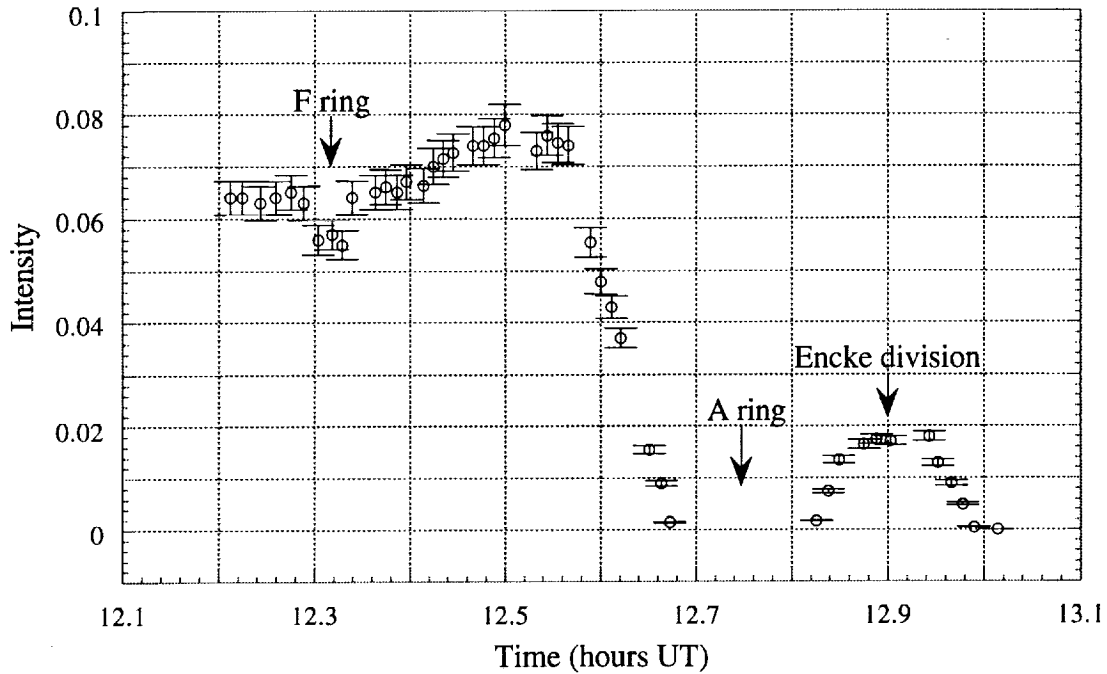
## **6. Titan**

New images of Titan have been recorded near its eastern elongation in November 1997. Obtained with the new 36-actuator UH AO system, these images taken in and out of the methane bands show both surface and atmospheric features with unprecedented resolution. These images will be processed and analyzed.

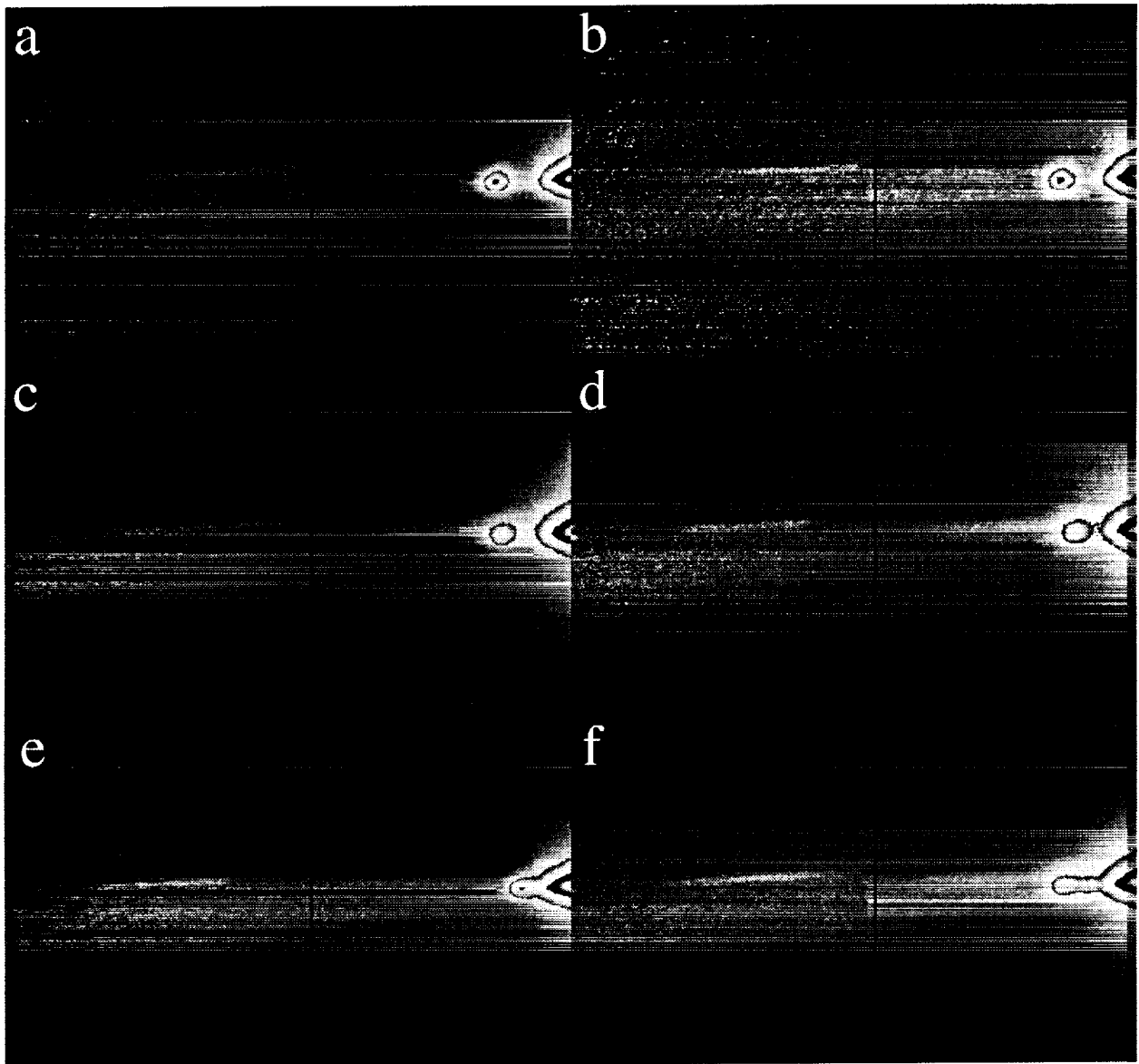
## **BUDGET**

Part of the grant has been used to cover the observational expenses (travel and stay for two runs on Mauna Kea), as well as computer charges (data reduction). Another part has been used to support an assistant specialist who has upgraded the IfA instrument. To continue this work, a similar level of support is necessary for the third year, for the same purpose: support of the instrument, of the observation runs, and of the data reduction.

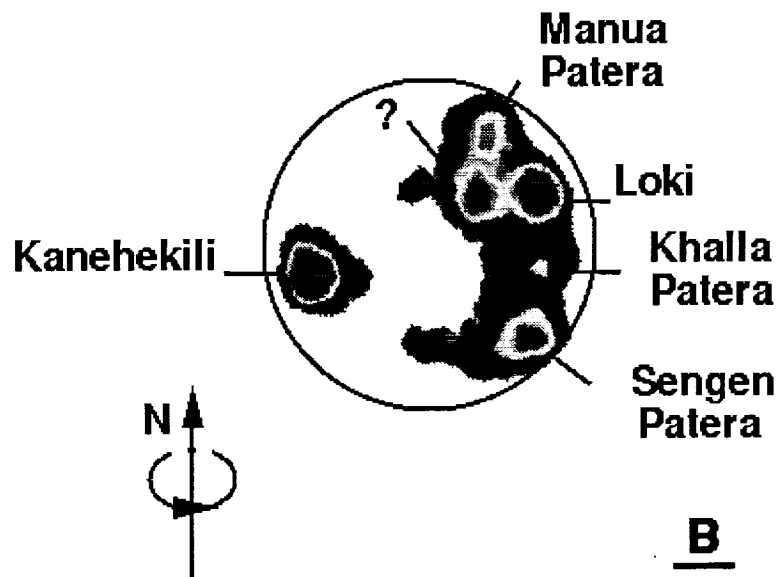
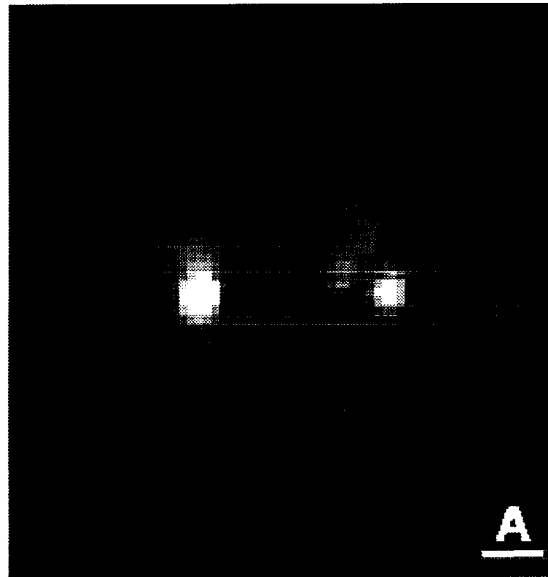




**Fig.1.** *Photometry of Epimetheus during an eclipse by the shadow of Saturn's rings.* Note that the F ring has an optically thin component and a dense core. The vertical optical depth of the thin part is estimated here to be  $5 \times 10^{-3}$ . Using the known size of the Encke gap as a calibration, the size of the dense core is estimated to be 30 km, in good agreement with Voyager observations. The distance from the center of Saturn to the core is found to be 141,100 km, a value larger than the maximum found by Voyager indicating a possible time evolution of the ring. From the timing of the observations one can estimate the inclination of Epimetheus' orbit to be  $22.5 \pm 1$  arcminute, a value consistent with but more accurate than the Voyager estimate of  $20.4 \pm 3$  arcminute.



**Fig. 2.** *Evidence for an arc of particules near Enceladus' orbit.* These adaptive optics images show light scattered beyond Saturn's main rings. Frames (a) to (e) form a time sequence with 10 minute intervals. Frame (f) is an average of them. Note the bright horizontal streak slightly above the ring plane. A dark vertical cursor has been drawn which coincide with the right edge of the streak on frame (a). Note the leftward motion of the streak on the following frames. Note that it also becomes shorter. The motion is consistent with that of an arc of particules on a Keplerian orbit close to that of Enceladus, but inclined by an angle of  $1.8^\circ$ . The arc is  $76^\circ$  ahead of Enceladus, i.e. near its leading Lagrange point. It appears to be a transient phenomenon possibly due to a collision between a large ice block ejected from Enceladus and ice fragments trapped near the Lagrange point.



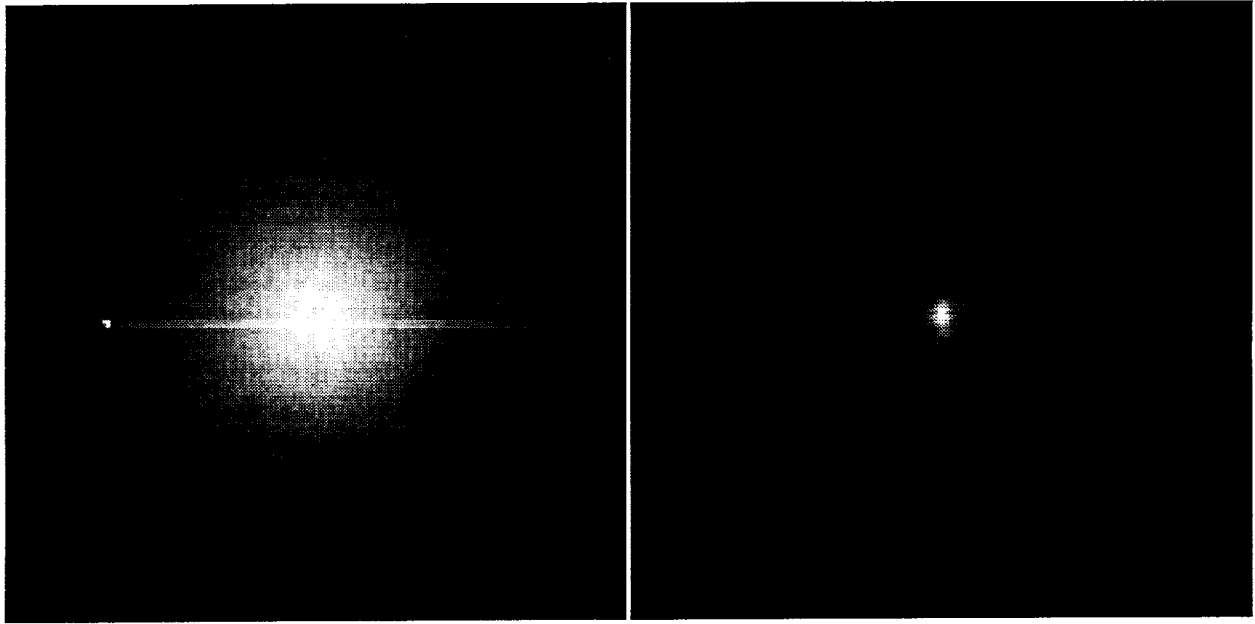
**Fig. 3.** *Volcanic activity on Io.* This adaptive optics images show the thermal emission of Io at 2.26  $\mu\text{m}$ . Europa (in visible sunlight) was used as a "guide" source for wavefront analysis while Io was in eclipse. *Image A* (top) is the sum of fourty recentered 4-sec exposures. *Image B* (bottom) is reproduced on a logarithmic scale to enhance the faintest sources on Io's surface. The image has been slightly rotated so that North is up and East is left. The bright volcano on the right is "Loki" and the hot-spot on the left is "Kanehekili". Other active regions on Io have been detected as well.



**Fig. 4.** *Neptune's stratospheric clouds and rotation.* These adaptive optics images of Neptune were taken in the K' band on October 25, 1996, at a 56-minute time interval. The planet angular diameter was 2.2 arc-second. Stratospheric clouds are clearly seen (above methane absorption). Longitudes of  $0^\circ$ ,  $\pm 30^\circ$ , and  $\pm 60^\circ$  are shown. The northern clouds are exactly located at  $30^\circ$  north, the southern ones are between  $32^\circ$  and  $48^\circ$  south. Meridians are shown centered on the middle spots of both the north and south clouds. The observed rotation period is close to 18 hours (compared to 16.1 hour measured from Neptune's radio emission). Observations extending over a longer time period will permit to establish the latitude dependence of the wind velocity and allow a comparison to be made with tropospheric wind velocities deduced from Voyager observations. Lower altitude clouds are also observable with adaptive optics in the J band.



**Fig. 5.** *Photometry of Pluto and Charon.* These adaptive optics images of Pluto and Charon were taken on June 14, 1997. Their angular separation was 0.9 arc-second. These images are 20-minute exposures taken through narrow band filters centered at 1.55  $\mu\text{m}$  (left image) and 2.25  $\mu\text{m}$  (right image). They show that Charon is indeed enriched in frozen  $\text{H}_2\text{O}$  compared to Pluto, as seen by its relative drop in brightness at 1.55  $\mu\text{m}$  compared to the continuum at 1.25  $\mu\text{m}$ .



**Fig. 6.** *The performance of the new 36-actuator UH AO system.* These I band ( $0.85\mu\text{m}$ ) images were obtained in November 1997 with the instrument mounted on the 3.6-m Canada France Hawaii telescope. The left image was taken with the system set to remove only static telescope aberrations. The right image was taken with atmospheric compensation turned on. Each image is the result of a 40 second exposure on a mag 10.5 star. The full width at half maximum of the compensated image is 68 milliarcsecond, an improvement by a factor ten over the uncompensated image. The improvement in peak intensity is by a factor 23.